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DRILLING AND GROUTING SUPPORT, PROJECT COWBOY.(U)
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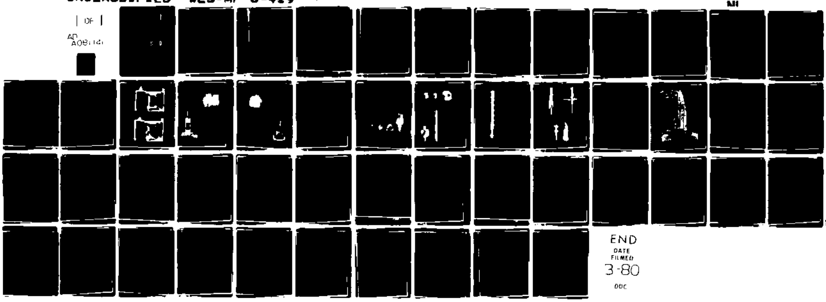

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# DRILLING AND GROUTING SUPPORT
# PROJECT COWBOY

MISCELLANEOUS PAPER NO. 6-419

March 1961

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

# PROJECT COWBOY, FINAL REPORT

# DRILLING AND GROUTING SUPPORT

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Bill J. Houston

U. S. Army Engineer Waterways
Experiment Station
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Vicksburg, Mississippi

March 1961

## ABSTRACT

In Project COWBOY, conducted to develop information on ground motion caused by underground explosions, high explosive (HE) charges were fired in two large spherical cavities, 12 and 30 ft in diameter, excavated in a salt mine, and the resulting ground motion was compared with that obtained when similar yield tamped HE charges were fired in the same general vicinity. The ground motion was measured by instruments embedded in the immediate and general area. This report describes drilling and grouting operations performed by the U. S. Army Engineer Waterways Experiment Station in connection with Project COWBOY. These operations included design of (a) saltgrouts for grouting instrument and for stemming HE shot holes drilled in the salt; (b) saltcrete for filling steel plugs used to seal the cavities; (c) saltgrout for grouting in place steel liners and walkways in access tunnels to the cavities; and (d) grouts for correcting for lost circulation of drilling mud in connection with the drilling of a 36-in.-diameter ventilation shaft into the mine. The Waterways Experiment Station also tested salt cores from the mine to determine their physical properties; furnished crews and equipment for drilling and grouting 10,629 ft of vertical, horizontal, and sloping holes of various lengths and diameters, for which special tools and techniques were developed; and determined in-place ultrasonic velocities of the salt near the cavities.

## PREFACE

The work performed by the U. S. Army Engineer Waterways Experiment Station (WES) in connection with Project COWBOY was accomplished in the fall and winter of 1959-1960 for the U. S. Atomic Energy Commission under the direction and coordination of the University of California Lawrence Radiation Laboratory. This report covers only the laboratory studies, field drilling, and field grouting phases of the project. Other phases will be reported by the responsible participating agencies.

It is desired to acknowledge the excellent cooperation, logistic support, and assistance furnished WES by the organizations and personnel participating in the Project COWBOY tests. Among these organizations were: U. S. Atomic Energy Commission, University of California Lawrence Radiation Laboratory, Holmes and Narver, Inc., Sandia Corporation, U. S. Bureau of Mines, and Carey Salt Company, Winnfield, Louisiana.

The WES phase of the over-all project was performed under the supervision of Messrs. J. M. Polatty, Project Officer, Thomas B. Goode, and Ralph A. Bendinelli, Assistant Project Officers, and W. O. Tynes, Bill J. Houston, K. L. Saucier, and Joe H. Sanderson. This report was prepared by Messrs. Polatty, Goode, Bendinelli, and Houston.

Col. Edmund H. Lang, CE, was Director, Mr. J. B. Tiffany, Technical Director, Mr. W. J. Turnbull, Chief of the Soils Division, and Mr. T. B. Kennedy, Chief of the Concrete Division of the WES at the time of the tests and publication of this report.

Publication of this report was delayed because the first draft and all illustrations were lost in a fire which occurred at WES on 3 October 1960. The report had to be completely rewritten, new photographs obtained, and new drawings prepared.

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CONTENTS (CONTINUED)

# PROJECT COWBOY, DRILLING AND GROUTING SUPPORT

## CHAPTER 1
## INTRODUCTION

### 1.1 PURPOSE OF PROJECT

The purpose of Project COWBOY was to determine just how effectively an underground explosion can be concealed. In theory, the most effective way of preventing detection of an explosion is to detonate it in the center of a spherical cavity underground where the explosion is decoupled from the surrounding medium, thus reducing the amount of energy transmitted to the medium. Information concerning this theory is vitally needed as the Geneva discussions on the banning of nuclear tests have pointed up the need for a foolproof technique that will enable an inspection team to locate a clandestine nuclear explosion.

Project COWBOY operations were conducted in the Carey Salt Mine, Winnfield, Louisiana, to develop information on ground motion caused by an underground explosion. To accomplish this, charges of high explosives (HE) were detonated in two large spherical cavities, one 12 ft in diameter and the other 30 ft in diameter, and the resulting motion was measured by instruments arrayed near the charges. In addition, comparative measurements were obtained of the earth motion resulting from detonation of tamped (coupled) charges of similar yield to those fired in the spheres. Overall layout of shot holes and instrument holes in the project area is shown in fig. 1.

### 1.2 SCOPE OF WATERWAYS EXPERIMENT STATION PROJECT COWBOY OPERATIONS

The Concrete Division of the Waterways Experiment Station (WES) was responsible for design of a saltgrout to be used for grouting instrument holes drilled in the salt. The instruments were to be used for measuring the velocity and intensity of the shock wave or earth motion induced by a controlled explosion in the halite formation. For the measurements to be accurate, the saltgrout was required to have very nearly the same characteristics as the surrounding salt as far as pulse velocity, density,

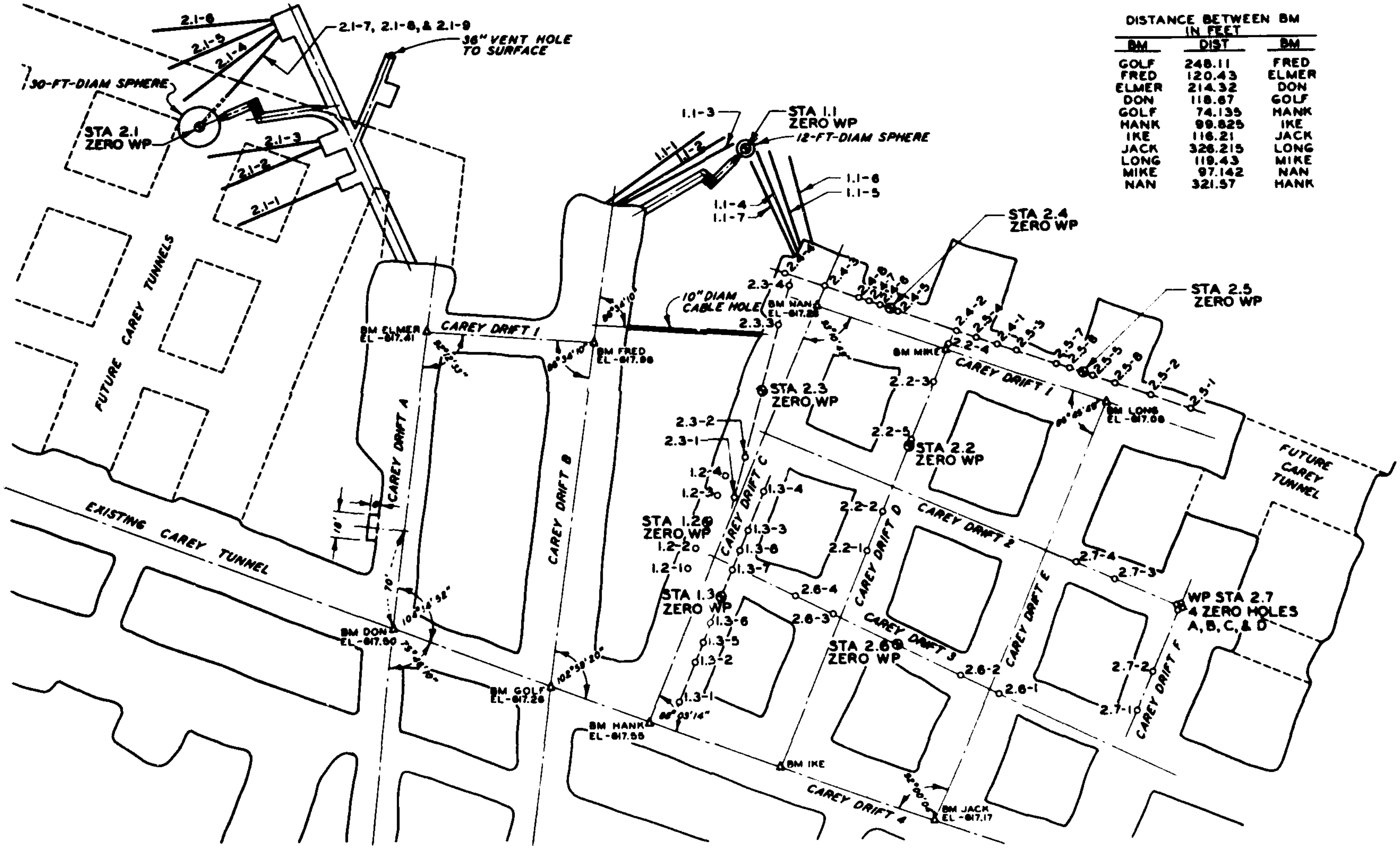



Fig. 1. Over-all layout of shot holes and instrument holes

strength, etc., were concerned in order not to affect the instrument readings. A grout of high early strength also was designed for grouting tamped pelletized HE in shot holes drilled in the salt; such shots are referred to as coupled shots (see fig. 2). In addition, a saltcrete was designed for filling steel plugs which were used to contain the uncoupled shots in the spherical cavities. Saltgrout was also used to grout in place steel liners for access tunnels to the cavities and steel walkway plates designed for ease of transporting the plugs into position. A number of grouts were designed for correcting for lost circulation of drilling mud during the drilling of a ventilation shaft from the surface into the mine by the Modern Foundation Company. The Concrete Division also tested salt cores obtained from the Carey mine to provide information on physical characteristics of the salt for the various agencies participating in Project COWBOY; the results of these laboratory tests are shown in Appendix B.

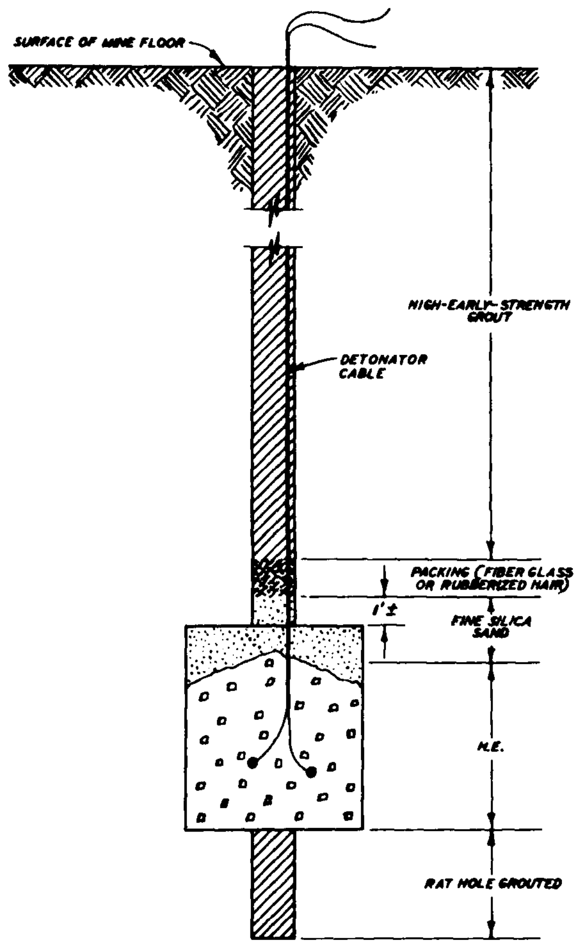



Fig. 2. Coupled shot hole

WES had a grouting crew at the job site during practically all of the COWBOY operations. This crew was responsible for and performed the actual grouting of all shot and instrument holes, the casting of the saltcrete plugs, and the grouting of the access tunnel liners and plug entrance walkways into the spheres, using laborers furnished by the Carey Salt Company. The WES crew also performed the lost-circulation grouting of the ventilation shaft whenever conditions were such that WES equipment could be utilized. When required grout volumes exceeded the capacity of the WES equipment, the Halliburton Oil Well Cementing Company was contracted to perform the actual pumping of the grout under the supervision of WES, using mixtures either designed or agreed to by WES.

At the request of the Sandia Corporation, in-place ultrasonic velocities were determined in the Carey Salt Mine and the results are shown in Appendix A.

The Soils Division of WES furnished drilling crews and equipment for drilling vertical, horizontal, and sloping holes of various lengths and diameters in the salt. A number of vertical holes, termed "shot holes," were terminated with right cylinders (see fig. 2). Initially, considerable modification and tooling were necessary to accomplish the varied and extensive drilling required to meet the close tolerances and rigid schedules. After the necessary tooling and modifications were accomplished, the schedules and tolerances were met as required during the remainder of the operation.

# CHAPTER 2

# LABORATORY INVESTIGATION

## 2.1 DESIGN CRITERIA

Proportioning studies using salt aggregates, both fine and coarse, in combinations with natural siliceous sand, an atomized aluminum powder, and a densifier disclosed that the in-situ physical characteristics of the salt formations of the Carey Salt Mine could be closely matched with saltcrete and saltgrout. The principal in-situ physical characteristic requirements were: a high compressive strength, a unit weight of 135 lb per cu ft, and a pulse velocity of approximately 14,000 fps.

## 2.2 MATERIALS

The following materials were used in the proportioning studies for either the saltcrete, saltgrout, or both.

| Material | Bulk Specific Gravity | Unit Weight (Solid) lb/cu ft | Absorption % |
|---|---|---|---|
| Portland cement, Type III | 3.15 | 196.24 | --- |
| Salt, mine fines | 2.25 | 140.18 | --- |
| Salt, fine | 2.19 | 136.24 | --- |
| Silica sand | 2.62 | 163.23 | 0.5 |
| Salt, fine, Grade C | 2.19 | 136.24 | --- |
| Salt, coarse, No. 1 | 2.19 | 136.24 | --- |
| Salt, coarse, No. 2 | 2.19 | 136.24 | --- |
| Aluminum powder | -- | -- | --- |
| Air-detraining agent | -- | -- | --- |

## 2.3 MIXTURES

The proportions finally selected for the saltgrout and saltcrete mixtures were:

| Material | 1-Bag-Batch Data: Solid Volume cu ft | 1-Bag-Batch Data: Saturated Surface Dry Weight, lb |
|---|---|---|
| | Saltgrout | |
| Cement | 0.479 | 94.00 |
| Salt, mine fines | 0.257 | 36.00 |
| Silica sand | 0.873 | 142.50 |
| Water | 0.802 | 49.97 |

(Continued)

| Material | 1-Bag-Batch Data: Solid Vclume cu ft | 1-Bag-Batch Data: Saturated Surface Dry Weight, lb |
|---|---|---|
| | Saltgrout (Continued) | |
| Brine salt | 0.137 | 19.26 |
| Aluminum powder | --- | (3.00 g) |
| Air-detraining agent | --- | (3.00 cc) |
| | Saltcrete | |
| Cement | 0.479 | 94.0 |
| Salt sands | 0.418 | 56.9 |
| Silica sands | 0.523 | 85.4 |
| Coarse salt, No. 2 | 0.627 | 85.4 |
| Coarse salt, No. 1 | 0.418 | 56.9 |
| Brine salt | 0.086 | 12.0 |
| Air-detraining agent | --- | (3.00 cc) |

## 2.4 TESTS OF SELECTED MIXTURES

The saltgrout and saltcrete mixtures selected for use were tested to determine their physical characteristics, and the results are given in the following subparagraphs. All test specimens of both the saltgrout and saltcrete were cured at an ambient temperature of 85 ± 2 F and relative humidity of 50 ± 2 percent. For some tests it was necessary to use non-standard methods, and these methods are described in the following subparagraphs.

2.4.1 Strength, Unit Weight, Ultrasonic Velocity, and Bond Strength to Salt. These characteristics were determined by standard tests except for unit weight and bond strength to salt. The unit weight was determined on hardened 6- by 12-in. cylinders. Due to the necessity of using these cylinders for compression tests and the tendency of the salt to go into solution, the unit weight was determined by weighing the specimen in air and then quickly in water in a nonsaturated condition. If it had been possible to use a saturated specimen, a slightly higher unit weight value would have been obtained.

Since attempts to drill cores for the bond strength test from the small salt samples secured at the job site were not successful, prisms 3-1/2 by 2-1/4 by 6 in. were sawed and used in this test. The bonding surface was cleaned and the specimen was placed in the bottom half of a form 3-1/2 by 4-1/2 by 6 in. in dimension. The top half of the form was then filled with saltgrout or saltcrete and the specimen was cured until tested. The specimens were tested in a modified shear test apparatus.

Results of the strength, unit weight, and sonic velocity tests were as follows:

| Test | Age, Days 3 | 7 | 14 | 21 | 28 |
|---|---|---|---|---|---|
| **Saltgrout** | | | | | |
| Compressive strength, psi | 1,930 | 1,840* | 2,400 | 2,650 | 2,800 |
| Unit weight (hardened), lb/cu ft | 134.5 | 135 | 135 | 135 | 135 |
| Flexural strength, psi | 535 | 695 | 735 | 780 | 845 |
| Ultrasonic velocity, fps | 11,100 | 11,300 | 11,500 | 11,650 | 11,800 |
| Tensile splitting strength, psi | 250 | 300 | 320 | 350 | 395 |
| Shear strength, static loading, psi** | 350 | 275* | 455 | 440 | 455 |
| Bond strength to salt, psi | -- | 215 | -- | -- | 290 |
| **Saltcrete** | | | | | |
| Compressive strength, psi | 4,090 | 4,370 | 4,570 | 4,780 | 4,880 |
| Unit weight (hardened), lb/cu ft | 135 | 135 | 134 | 134 | 135 |
| Flexural strength, psi | 670 | 415* | 490 | 485 | 540 |
| Tensile splitting strength, psi | 450 | 365* | 375 | 300 | 370 |
| Shear strength, static loading, psi | 475 | 410* | 460 | 460 | 385 |
| Bond strength to salt, psi | -- | 135 | -- | -- | 255 |

* Decrease in 7-day strength below that at 3 days attributed to loss of moisture by specimens following removal from molds at 3-day age.

** Figs. 3 and 4 show testing equipment and test specimen of saltgrout.

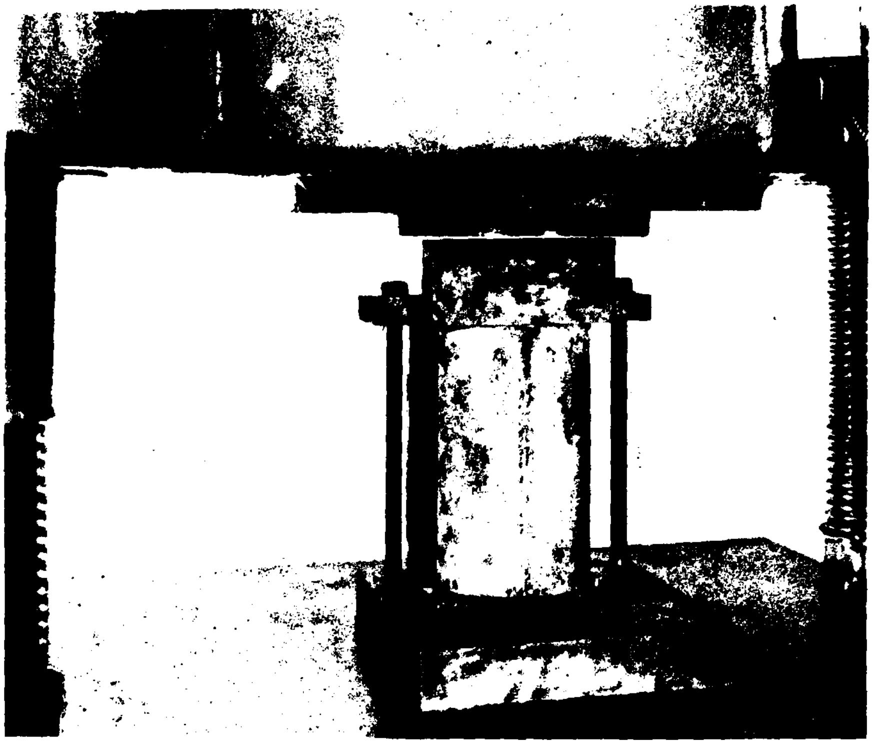


Fig. 3. Grout specimen positioned for static loading to determine resistance to shear

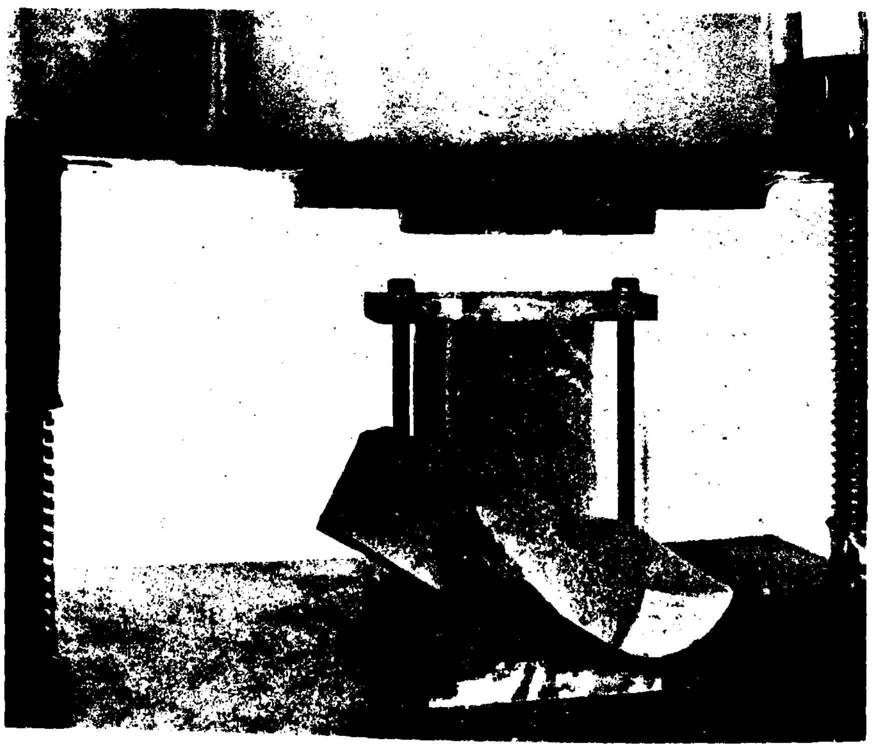


Fig. 4. Shear break of statically loaded grout specimen

2.4.2 Impact Shear Resistance. Beams 3-1/2 by 4-1/2 by 16 in. were cast and tested by dropping a 52-lb weight from various heights onto the cantilever-supported beam until failure occurred. The kinetic energy was calculated by multiplying the weight in pounds (52) by the distance, in feet, of the drop required to cause failure. The following values represent the average impact shear resistance of two test specimens tested at 7 days age and two specimens tested at 28 days age. Fig. 5 shows a sample of saltcrete after breaking.

Fig. 5. Typical break of specimen subjected to impact loading

| Drop in. | Impact Velocity fps | Kinetic Energy ft-lb |
|---|---|---|
| | Saltgrout | |
| 6 | 5.7 | 26 |
| | Saltcrete | |
| 6 | 5.7 | 26 |

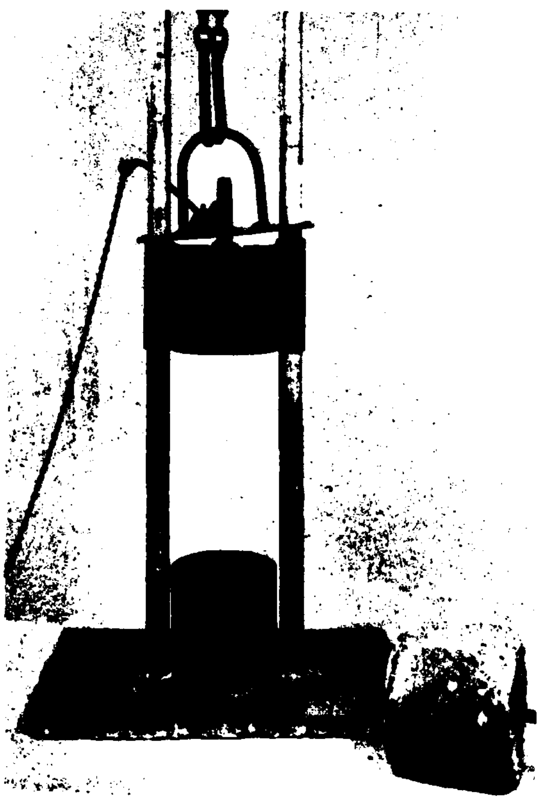


Fig. 6. Apparatus and test specimen used for determining bond strength of 1/2-in. rods to saltgrout by impact loading

2.4.3 Impact Bond to Steel. Specimens were made with 1/2-in.-diameter round steel rods extending through a 6- by 6-in. saltcrete cylinder and protruding 1 in. on each side. Fig. 6 shows the test equipment and a sal'grout test specimen. The bond was measured by determining the height that a 52-lb weight would have to fall from to move the rod 1/16 in. or more. The kinetic energy was determined as described in paragraph 2.4.2, and the resistance offered by the saltcrete can be determined by dividing the kinetic energy by the distance the rod moved. Fig. 7 shows a failed saltcrete test specimen.

Fig. 7. Typical break of specimen in determining bond strength of 1/2-in. rod

| Drop in. | Impact Velocity fps | Kinetic Energy ft-lb | 7-Day Movement in.* | 28-Day Movement in.* |
|---|---|---|---|---|
| | | Saltgrout | | |
| 6 | 5.7 | 26 | 0 | 0 |
| 12 | 8.0 | 52 | 0.09375 | 0.21875 |
| 18 | 9.8 | 78 | 0.375 | 1.0 |
| 24 | 11.3 | 104 | 0.875 | --- |
| | | Saltcrete | | |
| 6 | 5.7 | 26 | 0 | 0 |
| 12 | 8.0 | 52 | 0.1250 | 0.06250 |
| 18 | 9.8 | 78 | 0.3125 | 0.62500 |
| 24 | 11.3 | 104 | 0.8125 | 1.00000 |

* Average of two tests.

2.4.4 Resistance to Pull-Out. Steel rods 3/4 in. in diameter, deformed, round, and hooked, were tested in 8- by 8-in. saltcrete cylinders. The deformed and round rods extended through the cylinder, one end protruding approximately 1/2 in. and the other end approximately 30 in. Fig. 8 is an example of a test specimen.

| Load in 1000 lb | Avg Bond Stress psi | Net Movement of 3/4-in. Rods in. | | | |
|---|---|---|---|---|---|
| | | Deformed | | Plain | |
| | | 7 Day | 28 Day | 7 Day | 28 Day |
| | | Saltgrout | | | |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 212 | 0.0007 | 0.0027 | 0.0012 | 0.0062 |
| 8 | 424 | 0.0019 | 0.0049 | 0.0039 | 0.0104 |
| 12 | 636 | 0.0040 | 0.0071 | -- | 0.0166 |
| 16 | 848 | 0.0073 | 0.0103 | -- | -- |
| Yield-point load, lb | | 18,400 | 19,400 | 10,400 | 12,050 |
| | | Saltcrete | | | |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 212 | 0.0012 | 0.0007 | 0.0012 | 0.0012 |
| 8 | 424 | 0.0019 | 0.0024 | 0.0034 | 0.0029 |
| 12 | 636 | 0.0026 | 0.0036 | -- | 0.0041 |
| 16 | 848 | 0.0043 | 0.0062 | -- | 0.0083 |
| 20 | 1060 | 0.0059 | 0.0079 | -- | -- |
| Yield-point load, lb | | 22,400 | 21,700 | 11,600 | 16,800 |

Fig. 8. Deformed 3/4-in. rod embedded for determination of resistance to pull-out

# CHAPTER 3
# FIELD DRILLING

## 3.1 SCOPE

The field drilling performed by WES consisted of vertical, horizontal, and sloping holes of various lengths and diameters in the salt, with rigid tolerance requirements in respect to diameter, length, direction, and location of the termini of the holes. Cores of salt were obtained from some of the holes, and a number of the holes were underreamed to form right cylinders of various dimensions.

## 3.2 BACKGROUND

The locations for the holes were established in the field and assigned numbers and stations by survey parties working under the direction of the Project Officer. Instructions concerning the priority of drilling and the diameter, length, direction, and tolerance criteria for the holes were issued by the Project Officer on a day-to-day basis. The alignment of the holes was checked at frequent intervals by the survey parties as drilling progressed. The survey parties also examined the completed holes to determine the exact location of the termini of the holes and whether the holes met tolerance requirements in regard to alignment, diameter, and depth. All drilling was accomplished with rotary drilling equipment and methods, and compressed air was used for removing cuttings from the holes. Compressed air and electricity for drilling and lighting purposes were furnished by AEC.

## 3.3 DRILLING EQUIPMENT

With the exception of drill rods and core barrels, no commercial drilling equipment satisfactory for the drilling was available. As a result, considerable modification to commercially available drilling equipment and the development and construction of new equipment by WES were necessary to obtain the capabilities required to accomplish the varied and extensive drilling on schedule. The modified and new equipment which proved satisfactory, and with which approximately 95 percent of the drilling was accomplished, are described herein.

3.3.1 Drill Rigs. Two electrically powered, Sprague and Henwood Model 40-C, hydraulic-feed, skid-mounted drill rigs, and one air-powered, Joy Model H-15, screw-feed, post-mounted drill rig were used for all drilling. One Sprague and Henwood rig was powered with a 7-1/2-hp, 220-v motor equipped with a 2:1 reduction unit. The other Sprague and Henwood rig was powered with a 10-hp, 220-v motor equipped with a 3-speed transmission. The Joy rig was powered with a 16-hp, single-rotary type air motor. N-size (2-3/8-in. diameter) drill rods were used with the Sprague and Henwood rigs. A-size (1-5/8-in. diameter) drill rods were used with the Joy rig.

3.3.2 Drill Bits. Drill bits set with sharpened carboloy inserts, as shown in fig. 9, were used for drilling all holes. The 3-in.-diameter

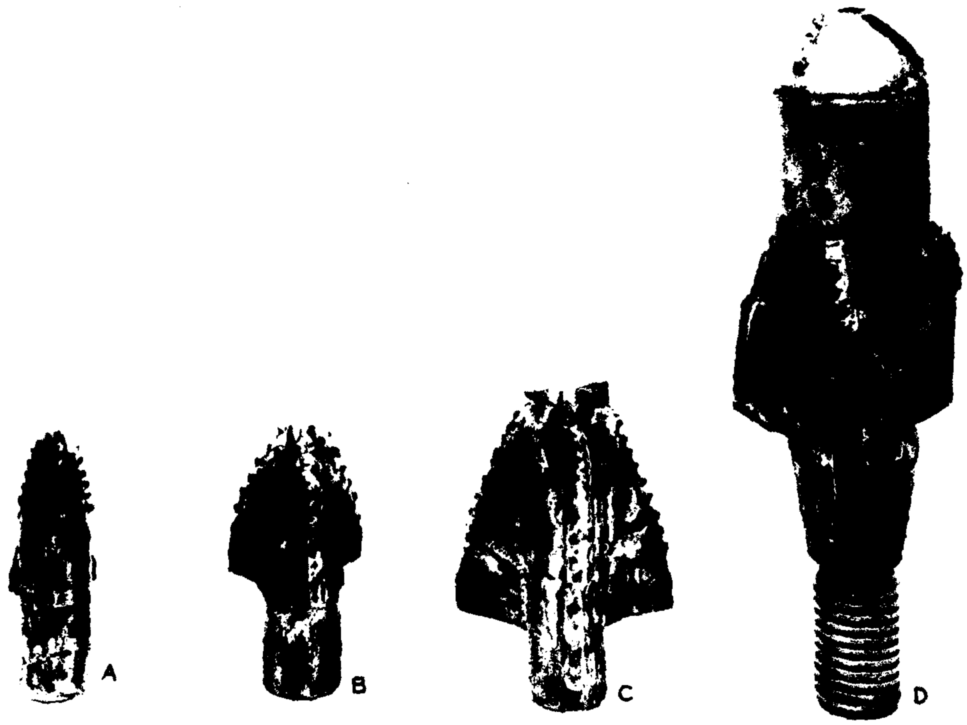



Fig. 9. Drill bits set with sharpened carboloy inserts. A. 3-in.-diameter pilot bit. B. 5-in.-diameter pilot bit. C. 8-in.-diameter reaming bit. D. 8-in.-diameter bullnose reaming bit

pilot bit (fig. 9A) was used for drilling 3-in.-diameter vertical and sloping holes, and pilot holes for 8-in.-diameter vertical holes. The 5-in.-diameter pilot bit (fig. 9B) was used for drilling 5-in.-diameter

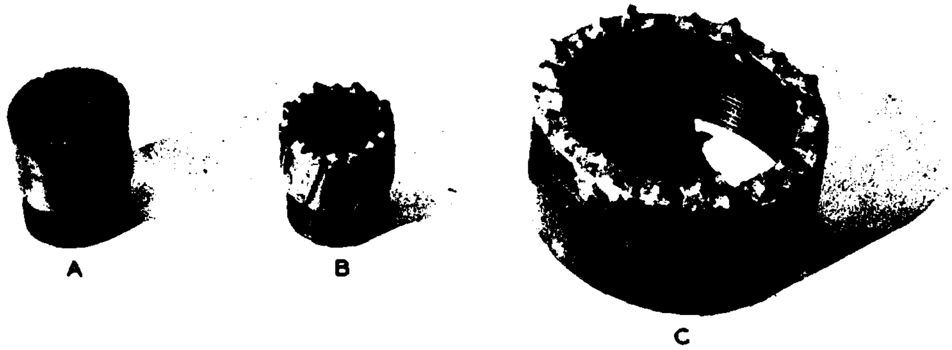



Fig. 10. Coring bits. A. NX diamond bit. B. NX bit set with sharpened carboloy inserts. C. 6- by 7-3/4-in. bit set with sharpened carboloy inserts

vertical holes and pilot holes for 8-in.-diameter horizontal holes. The 8-in.-diameter reaming bit (fig. 9C) was used for reaming 3-in.-diameter pilot holes to 8 in. in diameter. The 8-in.-diameter bullnose reaming bit (fig. 9D) was used for reaming 5-in.-diameter pilot holes to 8 in. in diameter.


Fig. 11. Drill rod guides. A. 8-in. diameter. B. 3-in. diameter

3.3.3 Coring Bits. The coring bits, shown in fig. 10, were attached to commercial double-tube core barrels, and were used to obtain cores of salt. The NX diamond bit (fig. 10A) and the NX bit set with sharpened carboloy inserts (fig. 10B) were used for obtaining 2-1/8-in.-diameter cores. The 6- by 7-3/4-in. bit set with sharpened carboloy inserts (fig. 10C) was used for obtaining 6-in.-diameter cores.

3.3.4 Drill Rod Guides. The drill rod guides shown in fig. 11 were used for stabilizing the

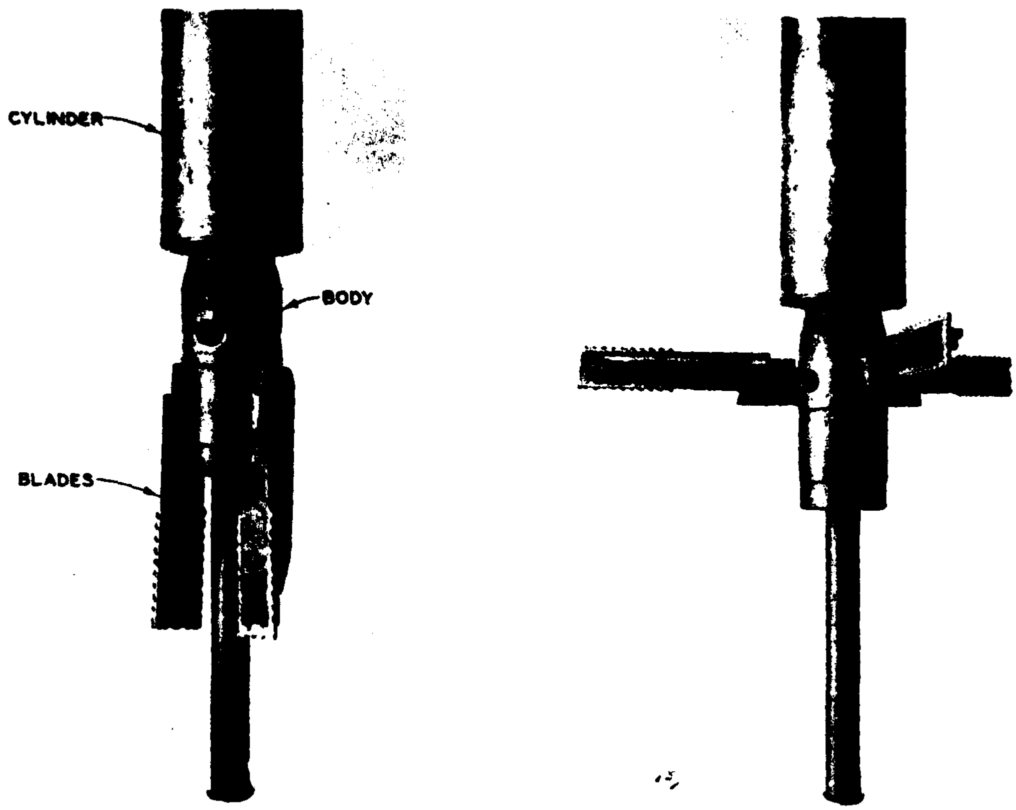
Fig. 12. Section of 5-in.-diameter continuous flight auger with pilot bit

drill rod string and the drill bits during drilling. The 8-in.-diameter guides, fig. 11A, were placed in the drill rod string at 20-ft intervals to prevent whip in the drill string when drilling 8-in.-diameter vertical or horizontal holes, or when underreaming. The 3-in.-diameter guide, fig. 11B, was run immediately behind the 3-in.-diameter pilot bit (fig. 9A) to control the alignment of the bit when 3-in.-diameter vertical or sloping holes were being drilled.

3.3.5 Continuous Flight Augers. The 5-in.-diameter continuous flight auger in 3-ft lengths, shown in fig. 12, was used for controlling the alignment of 5-in.-diameter vertical and horizontal holes.

3.3.6 Underreamer. The underreamer, fig. 13, was used for constructing right cylinders in borings. The reamer was equipped with carboloy insert blades of the lengths required for reaming holes from 8 to 16 in., 16 to 24 in., 24 to 36 in., and 36 to 42 in. The blades, fig. 13, are the size required for reaming holes from 24 to 36 in. in diameter. The cylinder of the reamer was 8 in. in outside diameter and 10 ft long. The reamer blades were expanded from the closed position to the open position by compressed air acting on a piston inside the cylinder.

3.3.7 Hawthorne Bit and Packer. The 11-in.-diameter Hawthorne bit, fig. 14A, was used for drilling 11-in.-diameter, 18-in.-deep holes for the installation of the packer, fig. 14B, to which nylon or cotton




a. Blades in closed position b. Blades in expanded position

Fig. 13. Underreamer


Fig. 14. A. Hawthorne drill bit, 11-in. diameter. B. Packer

duck dust collector bags were attached to collect dust created in drilling in the salt. The bags were about 30 in. in diameter and 70 ft long.

3.3.8 Compressed Air and Electrical Facilities. Compressed air for drilling in the mine was obtained from a 6-in.-diameter header pipe connected to five 500-cfm air compressors located aboveground near the mine shaft. Electricity for drilling purposes was available throughout the mine from conveniently located lines supplied from sources outside the mine.

3.3.9 Drill Pads. Concrete drill pads for supporting the skid-mounted drill rigs were constructed in pairs at the locations of most of the holes drilled with the skid rigs. The pads were about 12 in. wide, 12 in. high, and 5 ft long, with a 4-ft length of 3-in. steel angle embedded in the top.

## 3.4 DRILLING PROCEDURES

The drilling, coring, and underreaming were performed by means of the previously described drill rigs and accessory drilling equipment, using compressed air for removing cuttings from the holes. The two Sprague and Henwood skid-mounted drill rigs were used for drilling, coring, and/or underreaming operations in 133 of the 139 holes drilled. The Joy post-mounted drill rig was used for drilling the other 6 holes.

3.4.1 Drill Rig Setup. At each hole location, the drill rig to be used was set up, oriented, and aligned for drilling in the desired direction by means of a transit, and then rigidly anchored in place before drilling was started. The Joy drill was anchored by embedding the top of the mounting post in the roof of the mine and the bottom of the post in the floor of the mine. At the locations where concrete drill pads were constructed, the Sprague and Henwood drill rigs were anchored in place by welding the steel skids of the rigs to the steel angles in the top of the concrete pads. At other locations, the Sprague and Henwood rigs were anchored by means of steel bolts embedded in the floor of the mine. At all locations the Sprague and Henwood rigs were braced against the mine roof with a pipe column. After the drill rig was set up, a packer was installed and connected to a dust collector bag; then drilling, reaming, coring, and underreaming operations were accomplished as required. A typical setup for the skid-mounted drill rig is shown in fig. 15.

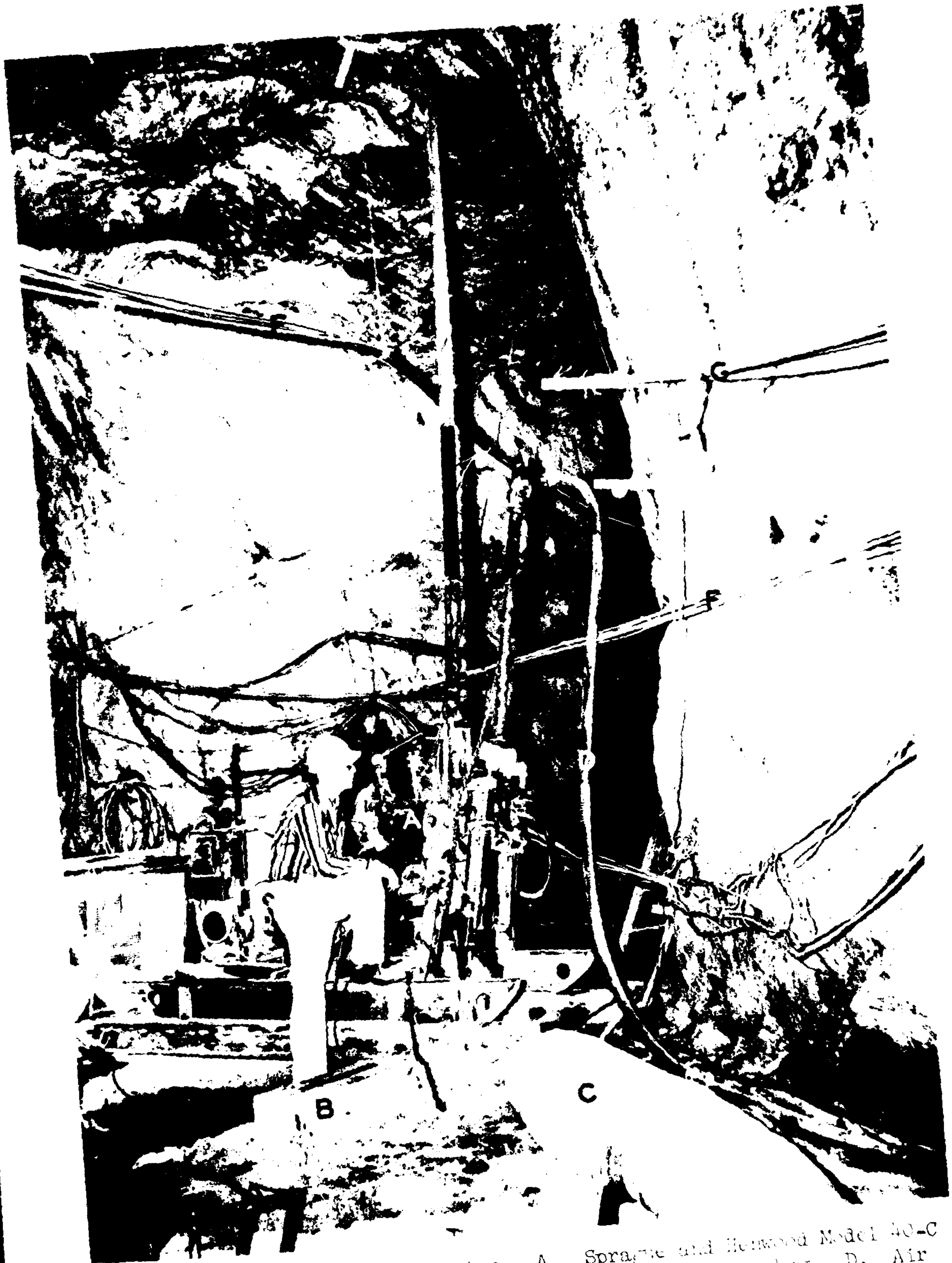



Fig. 15. Typical drill rig setup. A. Sprague and Henwood Model 40-C drill rig. B. Concrete drill pad. C. Dust collector bar. D. Air supply line. E. Pipe column brace. F. Electric power lines to drill rig, 220 v. G. Electric light line, [illegible]

3.4.2 Drilling 3-in.-Diameter Holes. Vertical and sloping 3-in.-diameter holes, and vertical and sloping 3-in.-diameter pilot holes that were subsequently reamed to 8 in. in diameter were drilled with the 3-in.-diameter bit shown in fig. 9A attached to a 10-ft length of the 3-in.-diameter drill rod guide shown in fig. 11B. The bit was rotated at about 200 rpm, and light bit pressures were used as it was found that heavy bit pressures caused undesirable deviations in the alignment of the holes. Drilling speed with the 3-in.-diameter bit ranged from 15 to 28 ft per hr.

3.4.3 Drilling 5-in.-Diameter Holes. Vertical holes of 5-in. diameter and pilot holes for 8-in.-diameter horizontal holes were drilled with the 5-in.-diameter bit and the continuous flight auger shown in fig. 12. Sections of the flight auger were added to the drill string as the holes were advanced. The maximum length of flight auger used was 27 ft. When 5-in.-diameter holes exceeded a depth of 27 ft, N-size drill rods were added to the drill string as required. The 5-in.-diameter bit and auger assembly was rotated at about 100 rpm, and heavy bit pressures were used. Drilling speed ranged from about 10 to 15 ft per hr. No trouble was experienced in maintaining alignment of the vertical holes or the lateral alignment of the horizontal holes. However, some trouble was experienced in maintaining the vertical alignment of several of the horizontal holes. Whenever excessive vertical deviation in alignment occurred, drilling of the pilot hole was stopped. The hole was then reamed to a diameter of 8 in. and the alignment of the hole corrected through the use of heavy drill collars and 8-in.-diameter drill rod guides. After the alignment of the hole was corrected, drilling of the pilot hole was resumed.

3.4.4 Reaming Holes to 8-in. Diameter. The 8-in.-diameter reaming bits shown in fig. 9C and D were used for reaming 3-in.- and 5-in.-diameter pilot holes, respectively, to a diameter of 8 in. As the hole was advanced, drill rod guides (fig. 11A) were placed in the drill rod string at 20-ft intervals to stabilize the drill string. Relatively light bit pressures were used, and the bit was rotated at approximately 100 rpm.

3.4.5 Underreaming. Holes in which right cylinders were constructed were initially drilled to a diameter of 8 in. and extended to a depth of 40 to 60 ft below the elevation of the bottom of the cylinder to provide a "rat" hole for the cuttings resulting from reaming operations. The under-reamer with the cutter blades in the closed position as shown in fig. 13a was then lowered into the hole to the elevation of the top of the zone to be reamed. Compressed air was then forced into the reamer cylinder and the blades were slowly expanded as the reamer was rotated. After the blades were fully expanded as shown in fig. 13b, the rotation was continued, the reamer was lowered slowly, and the cylinder was reamed to the required bottom elevation. Initially all cylinders were reamed to a diameter of 16 in. for the full length of the cylinder and then successively reamed to diameters of 24, 36, and 42 in. as required. The reamer was rotated relatively slowly, about 40 rpm, and fed by gravity; otherwise, the blades tended to grab. After each increment of reaming, a lightweight, 3-in.-ID pipe was lowered into the rat hole and the salt cuttings were blown out by means of compressed air.

3.4.6 Coring. All core drilling in the salt was performed with the previously described core barrel, diamond bits, and coring bits set with carboloy inserts. The NX core barrel was rotated at about 200 rpm, and the 6- by 7-3/4-in. core barrel was rotated at about 50 rpm. Low bit pressures were used with both core barrels. The length of core runs varied from 1 to 5 ft, depending on the length of core required.

### 3.5 SUMMARY OF DRILLING PROGRAM

A total of 10,629 ft of drilling was accomplished in the drilling of 139 holes that ranged from 2 to 266 ft in length. About 3 ft of NX cores and 60.6 ft of 6-in.-diameter cores were obtained from six of the holes. Twelve holes were terminated with right cylinders of various lengths (14 to 80 in.) and diameters (16 to 42 in.). The depths and diameters of all holes drilled, together with the radial deviations of the terminal ends of the holes from the objective locations, are shown in tables 1 through 5. It will be noted in table 1 that three holes were drilled as replacements for holes (26, 41, 42) which did not meet alignment tolerances.

# CHAPTER 4
# FIELD GROUTING

## 4.1 EQUIPMENT

The following major items of grouting equipment were used in surface and/or subsurface grouting operations:

Two Wagner steam simplex pumps, air operated.

One Gardner-Denver duplex pump, air operated.

Two 5-cu-ft-capacity, tub-type grout mixers, air operated.

One 4-cu-ft-capacity, tub-type grout mixer, electrically operated.

One Colcrete drum-type grout mixer, 8-cu-ft capacity, gasoline operated.

One conventional concrete mixer, 4-cu-ft capacity, electrically operated.

One conventional 10-S concrete mixer, gasoline operated.

Grout injection hoses, both rubber and plastic, ranging from 3/4 in. to 2 in. in inside diameter (ID).

## 4.2 SUBSURFACE GROUTING AND CONCRETING PROCEDURES

For accomplishing the grouting for horizontal, vertical, and sloping holes, for the steel tunnel liners, cylindrical and rectangular plugs, walkways and walkway floor plates for entry of plugs, and miscellaneous grouting, the following procedures were employed.

<u>4.2.1 Instrument and Shot Holes.</u> To grout the instrument holes, either one or two grout mixers were used with one of the simplex pumps, the latter equipped with 3/4-in.-ID or 1-in.-ID injection hoses. All instrument hole grouting was done at a slow rate of pumping. In the case of the horizontal and sloping holes the 3/4-in. injection and relief hoses were introduced into the holes and grouted in place at the entrances of the holes by means of a quick-set cement "dry pack," used as a packer, and the hoses were left in the holes following the injection of the grout. The hoses were withdrawn from the vertical instrument holes as the grout filled the hole.

The shot holes were grouted with a pumpable, quick-set, Cal-Seal-portland cement mixture. To prevent this grout from penetrating the voids in the pelletized HE, prior to grouting, the foot of hole immediately above the HE was stemmed with a fine-graded siliceous sand. All holes containing water were dewatered by means of an old-fashioned type well bucket and large sponges 12 ± 4 hr prior to grouting.

4.2.2 Tunnel Liners. Following placement and welding of the tunnel liners in the access tunnels to both spheres, the ends of the areas between the outside of the liners and the tunnel walls that were to be grouted were dry-packed approximately 2 hr prior to grouting. Two simplex pumps and two tub mixers were operated simultaneously to grout in place the liner for the access tunnel to the 12-ft sphere. This liner was grouted in two sections, the second section being grouted a few weeks after the first. The time required for grouting of the first and second sections was approximately 6 and 4 hr, respectively. The duplex pump and two tub mixers were used to grout the liner for the access tunnel to the 30-ft sphere, which was accomplished in one operation requiring approximately 8 hr.

4.2.3 Plug Entry Walkways. The plug entry walkway for the 12-ft sphere was grouted with the same equipment used for grouting the liner for the access tunnel to this sphere. The 30-ft sphere plug entry walkway was grouted with the same equipment used to grout the liner for the access tunnel to this sphere.

4.2.4 Walkway Floor Plates. A special low-pressure injection nozzle was designed for the grouting of the steel floor plates for the plug entry walkways to the respective spheres. Only one tub mixer and one simplex pump were required for this grouting.

4.2.5 Sphere Plugs. With the exception of the smaller cylindrical plug for the smaller sphere, all cylindrical plugs used for plugging the cylindrical sections of the access tunnels, one each located at the immediate entrance to each sphere, were grouted using saltgrout. Much difficulty was experienced in righting the first of the smaller cylindrical plugs for saltcreting due to its enormous weight. Since the saltgrout had developed a compressive strength of approximately 3300 psi when used in subsurface work (see paragraph 4.3), it was decided to use grout in the remainder of the cylindrical plugs as pumping would not require righting the plugs. The five rectangular plugs, used for plugging the rectangular section of the access tunnels, when placed on the entry walkway for the larger sphere, afforded no overhead space for filling with saltcrete. Since there were a number of 9- by 9- by 9-in. 3500-psi concrete blocks already at the job site and available for miscellaneous construction, it was decided in a conference of all concerned to utilize these blocks for filling the rectangular plugs. This was done by pre-placing, with approximately 1-in. spacing, successive layers of the blocks in each of the plugs as grouting progressed. Placed horizontally between each layer of blocks was a pattern of 3/8-in.-diameter deformed reinforcing rods.

## 4.3 COMPRESSIVE STRENGTH OF SUBSURFACE GROUT SPECIMENS

Compressive strength tests of field specimens made from the grouts used in the underground work gave the following results:

| Grout | Compressive Strength (psi) at Indicated Age (Days) | | | |
|---|---|---|---|---|
| | 1 | 2 | 7 | 28 |
| Saltgrout,* psi | 1100 | 2000 | 2800 | 3300 |
| Quick-set grout,** psi | 1450 | 2500 | 2700 | 3100 |

* Used for grouting instruments, liners, plugs, plug entry walkways and plates, drill pads, and miscellaneous work.

** Used for grouting shot holes and miscellaneous work.

## 4.4 VENTILATION SHAFT GROUTING

The extent of grouting by WES and the equipment, procedures, and mixtures used in performing grouting in connection with the drilling of the 776-ft-deep, 36-in.-ID, steel-cased ventilation shaft were as follows.

<u>4.4.1 Equipment Arrangement.</u> The conventional 10-S concrete mixer and the duplex pump were used for the majority of the grouting work done by WES for the ventilation shaft. Initially the Colcrete mixer was employed; however, charging difficulties resulted in insufficient production. The duplex pump, with a fluid end pressure of approximately 300 psi and a pumping capacity of approximately 30 cu yd per hr, was equipped with a 2-in.-ID injection hose which was coupled to the vertical mud line of the Modern Foundation Co. drill rig. This arrangement provided

the means for pumping grout through the drill stem to any desired location in the hole.

4.4.2 Cap Rock Formation Grouting. During the drilling in September and October of the upper 200 ft of the 9-in.-diameter pilot hole, WES grouted six times to correct for lost circulation of drilling mud. Each of the six groutings required from 2 to 6 cu yd of neat and/or sanded grout, depending on the type of lost circulation that occurred. The fact that the redrilling and reaming operations to increase the diameter of the hole to 42 in. did not result in loss of drilling mud until the aquiferous area at about the 416-ft depth was reached speaks well for the effective penetration and sealing effect of these six grouting operations.

Between approximately the 390- and 410-ft depths of the pilot hole, 19 losses of drilling mud circulation were experienced. For these losses, WES conducted 15 groutings in this area using neat and sanded grouts in quantities ranging from 1 to 16 cu yd. The Halliburton Oil Well Cementing Co. grouted the other four of these losses using neat-cement grouts containing either Cal-Seal, fly ash, diesel oil, or gilsonite, the latter for bridging. A 6-in.-diameter, drillable, squeeze-type packer was used in pressure-pumping three of these four mixtures with pumped quantities ranging from 2-1/2 to 16 cu yd. The nineteenth grouting was conducted by WES to provide a quick-set grout plug in this lost-circulation area in order to permit subsequent reamings to 42 in. in diameter above the area. In the meantime, further studies were made in regard to sealing off what appeared to be a large, cavernous aquifer of indeterminate size, partly porous, and containing permeable and impermeable seams of halite, anhydrite, and silty clay.

4.4.3 Pressure Grouting for Lost Circulation. In order to pressure grout for lost circulation during the 42-in. reaming, WES developed a method for placing grout plugs a few feet above the lost-circulation area by introducing water-inflated rubber balls immediately above the area to prevent the freshly pumped plug grout from entering the area. After setting of the grout, a 6-in.-diameter hole was drilled through the plug and a squeeze-type, 6-in., drillable packer was placed in the hole. During the reaming operation which extended the diameter of the hole from 9 to 42 in., 18 groutings for correcting for lost circulation in the vicinity of the 400-ft depth were performed by WES or by Halliburton under the supervision of WES. The quantities of neat-cement grout used ranged from a few cubic yards to as much as 75 cu yd per grouting.

Prior to running 40-in.-ID casing some few feet beyond the lost-circulation area, a grout plug for containing a 6-in. packer and grouting shoe at the lower end of a section of this 40-in.-ID casing was pumped by WES. The grouting of this casing in place and the last grouting for lost-circulation, conducted in January 1960 following the placement of the casing, was done by Halliburton under the supervision of WES. The quantities of materials used for grouting through the annulus from the top of the casing were: 8650 sacks of portland cement, Type I; 500 sacks of Pozzmix; and 756 sacks of Aquagel. The quantities used in grouting through the packer and shoe at the bottom of the casing were: 3373 sacks of portland cement, Type I; and 738 sacks of Cal-Seal.

4.4.4 Lost-Circulation Grout Mixtures. The three basic grout mixtures used by WES in this grouting were as follows:

| Material | | Weight, lb | Volume, cu ft |
|---|---|---|---|
| | | Mixture No. 1, 1-Bag Batch | |
| Cement, Type III | | 94.0 | 0.479 |
| Silica sand | | 72.0 | 0.441 |
| Aluminum powder | | (5.0 g) | (-) |
| Water | | 47.0 | 0.754 |
| Fine salt* | | 17.0 | 0.121 |
| | Total | 230.0 | 1.795 |
| | | Mixture No. 2, 1-Bag Batch | |
| Cement, Type III | | 94.0 | 0.479 |
| Aluminum powder | | (5.0 g) | (-) |
| Water | | 47.0 | 0.754 |
| Fine salt* | | 17.0 | 0.121 |
| | Total | 158.0 | 1.354 |
| | | Mixture No. 3, 2-Bag Batch | |
| Cement, Type III | | 188.0 | 0.958 |
| Cal-Seal | | 100.0 | 0.584 |
| Water | | 167.0 | 2.681 |
| | Total | 455.0 | 4.223 |

* Salt for brining mixture water used only when drilling returns indicated salt present.

The results of compressive strength tests of field specimens* were:

| Mixture No. | Compressive Strength (psi) at Indicated Age (Days) | | | |
|---|---|---|---|---|
| | 1 | 2 | 7 | 28 |
| 1 | 1200 | 2000 | 2600 | 2800 |
| 2 | 900 | 1500 | 1900 | 2400 |
| 3 | 1100 | 2500 | 2700 | 2900 |

4.4.5 Grouting of Casing. After the ventilation shaft had been drilled to a depth of approximately 776 ft, a 36-in.-ID steel casing was lowered and plans were made to grout the casing in place by means of a Baker duplex float cementing shoe and Baker stinger. A casing head pack-off was provided consisting of a 5/8-in.-thick by 36-in.-ID flanged and dished head with connections for a 4-1/2-in. drill pipe for grout injection. There were also 4-in. line pipes for circulating 17.5-lb-per-gal mud. The thick mud was left in the casing during the grouting operations to prevent possible collapse of the casing. Immediately prior to the grouting performed by Halliburton, the casing was pressurized to 50 psi and saturated brine was circulated through the drill pipe and around the casing for 30 min to flush out the annulus. The mixture used was Halliburton's standard 50-50 Pozzmix "A" with 2 percent Howcogel, 1 g of aluminum powder per cubic foot, and fine salt mixed into the cement in the proportion of 3.1 lb of salt per gallon of mixing water. The cement slurry contained 5.75 gal of water per cubic foot of cementing material. A defoaming agent and a carnotite radioactive tracer were added. Grout was pumped at the rate of 600 to 800 cu ft per hr at pressures of 50 to 100 psi. WES representatives continually monitored the mixing operations to ensure maintenance of uniform grout. After cement returns were noted at the surface, pumping was continued for 45 min. Material used totaled 810 bags cement, 810 bags Pozzmix "A," and 27 bags Howcogel, plus salt and aluminum powder.

The pressure of 75 psi on the casing was maintained until WES advised that initial set had occurred at about 10 hr after pumping.

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* Average strengths of two or more 2-in. cube specimens cast from grouts during pumping operations.

Tests conducted by WES on samples of grout secured during the pumping operations gave the following compressive strengths:

| Age | Compressive Strength, psi* |
|---|---|
| 35 hours | 225 |
| 7 days | 1890 |
| 28 days | 2500 |

* Average of three 2-in. cube specimens for each age.

# CHAPTER 5
# DISCUSSION AND CONCLUSIONS

## 5.1 UNDERGROUND DRILLING AND GROUTING

Initially, a considerable amount of modification, tooling, and retooling was necessary to accomplish the varied and extensive drilling required to meet the close tolerances and rigid schedules. However, after the first two weeks during which the necessary tooling and modifications were accomplished, no major problems were encountered and schedules and tolerances were met as required during the remainder of the operation. Time lost due to breakdowns, maintenance, etc., was considered normal for the operating conditions to which the equipment was subjected. Out of a grand total of 10,629 ft of 3-, 5-, and 8-in. holes drilled, it was necessary to redrill only 331 ft, consisting of three 8-in.-diameter holes. This represents approximately 3 percent of the total footage drilled. The procedures and techniques employed in the underground drilling and grouting operations were successful in achieving the desired results. The type, size, and weight of both the drilling and grouting equipment, with minor exceptions, appeared to be well suited to this type of work. In spite of all-but-inaccessible areas, crowded working conditions, inexperienced support labor, need for haste, and general hindering activity, it is believed that all of the varied underground drilling and grouting was successful and met job specifications. No major problems were experienced during the grouting of the instrument and shot holes, tunnel liners, plugs, entry plug walkways, walkway floor plates, and miscellaneous work. However, the inexperienced labor assisting with the grouting work required constant and close supervision and did quite frequently, in spite of the close supervision, hamper the progress of the work.

## 5.2 VENTILATION SHAFT GROUTING

It is believed that most of the ventilation shaft problems were results of inexperience in drilling this type of hole and also of the meager knowledge available as to the composition of the aquiferous formation existing between the cap rock and salt formations. The fact that the redrilling and subsequent reaming operations above the aquifer did not result in loss of drilling mud speaks well for the effective penetration and sealing effect of the grouting performed in this area. The method developed of placing grout plugs for containing standard 6-in. packers above a lost-circulation area proved highly successful in making pressure grouting possible.

## 5.3 PERSONNEL PHASING

Personnel phasing varied with the work load. Three drilling crews consisting of a total of 10 personnel were assigned during peak drilling operations. However, the majority of the drilling required only two crews totaling seven personnel. Peak grouting operations, which were performed during the latter part of December and the early part of January, required eight WES personnel. Five personnel were assigned during normal grouting operations which consisted mostly in grouting underground instrument and shot holes. Supervisor's tours for both the drilling and the grouting ranged from one week to one month in most cases, and for practically the duration of the work in a few instances. Nonsupervisory personnel tours averaged approximately six weeks.

Table 1

Field Drilling, Vertical Instrument Holes

| No. | Station | Diameter in. | Depth ft | Deviation* ft | No. | Station | Diameter in. | Depth ft | Deviation* ft |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.2-1 | 8 | 54.5 | 0 | 30 | 2.4-8 | 8 | 121.0 | 3.16 |
| 2 | 1.2-2 | 8 | 54.5 | 0.25 | 31 | 2.4-9 | 8 | 51.0 | 0.34 |
| 3 | 1.2-3 | 8 | 54.5 | 0.25 | 32 | 2.4-10 | 3 | 31.0 | 0.36 |
| 4 | 1.2-4 | 8 | 54.0 | 0.35 | 33 | 2.4-11 | 3 | 21.0 | 0.70 |
| 5 | 1.3-2 | 8 | 55.0 | 0.00 | 34 | 2.4-12 | 3 | 21.0 | 0.13 |
| 6 | 1.3-3 | 8 | 55.0 | 0.13 | 35 | 2.4-15 | 8 | 121.0 | 0.76 |
| 7 | 1.3-4 | 8 | 55.0 | 0.27 | 36 | 2.4-16 | 3 | 111.0 | 0.18 |
| 8 | 1.3-5 | 8 | 55.0 | 0.27 | 37 | 2.5-1 | 8 | 119.0 | 3.09 |
| 9 | 1.3-6 | 8 | 55.0 | 0.03 | 38 | 2.5-2 | 8 | 120.5 | 2.41 |
| 10 | 1.3-7 | 8 | 55.5 | 0.29 | 39 | 2.5-3 | 8 | 119.5 | 2.38 |
| 11 | 1.3-8 | 8 | 55.5 | 0.31 | 40 | 2.5-4 | 8 | 119.5 | 1.04 |
| 12 | 2.2-1 | 8 | 119.0 | 0.61 | 41 | 2.5-5 | 8 | 110.0 | 2.34 |
| 13 | 2.2-2 | 8 | 119.0 | 0.17 | 42 | 2.5-5 | 8 | 110.0 | 2.40 |
| 14 | 2.2-3 | 8 | 120.0 | 1.70 | 43 | 2.5-5 | 8 | 110.0 | 0.35 |
| 15 | 2.2-4 | 8 | 120.5 | 1.51 | 44 | 2.5-6 | 8 | 110.0 | 1.33 |
| 16 | 2.2-5 | 8 | 110.0 | 0.78 | 45 | 2.5-7 | 8 | 110.0 | 1.21 |
| 17 | 2.2-8 | 8 | 109.0 | 0.29 | 46 | 2.5-8 | 8 | 120.0 | 2.93 |
| 18 | 2.3-1 | 8 | 119.5 | 1.38 | 47 | 2.6-1 | 8 | 119.0 | 0.38 |
| 19 | 2.3-2 | 8 | 120.0 | 0.16 | 48 | 2.6-2 | 8 | 120.0 | 0.38 |
| 20 | 2.3-3 | 8 | 120.0 | 0.34 | 49 | 2.6-3 | 8 | 120.0 | 0.35 |
| 21 | 2.3-4 | 8 | 119.5 | 0.34 | 50 | 2.6-4 | 8 | 120.0 | 0.57 |
| 22 | 2.4-1 | 8 | 120.5 | 2.37 | 51 | 2.6-7 | 8 | 108.0 | 0.80 |
| 23 | 2.4-2 | 8 | 120.5 | 0.91 | 52 | 2.6-8 | 8 | 109.0 | 0.31 |
| 24 | 2.4-3 | 8 | 121.0 | 0.36 | 53 | 2.7-1 | 8 | 208.5 | 1.56 |
| 25 | 2.4-4 | 8 | 120.5 | 0.78 | 54 | 2.7-2 | 8 | 209.5 | 1.23 |
| 26 | 2.4-5 | 8 | 111.0 | 2.59 | 55 | 2.7-3 | 8 | 210.0 | 0.96 |
| 27 | 2.4-5 | 8 | 111.0 | 0.57 | 56 | 2.7-4 | 3 | 150.0 | -- |
| 28 | 2.4-6 | 8 | 111.0 | 2.81 | 57 | 2.1-17 | 8 | 25.0 | 0.04 |
| 29 | 2.4-7 | 8 | 111.0 | 1.59 | | | | | |

Note: Holes 27 and 42 were drilled as replacements for holes 26 and 41, respectively, which did not meet tolerance requirements. Hole 43 was drilled as a replacement for hole 42 which also did not meet tolerance requirements.

* Radial distance between terminus of hole and planned terminus measured normal to axis of hole.

Table 2

Field Drilling, Vertical Shot Holes

| No. | Station | Diameter in. | Depth ft | Deviation* ft | Underreaming Diameter in. | Underreaming Depth, ft From | Underreaming Depth, ft To |
|---|---|---|---|---|---|---|---|
| 1 | 1.2 | 8 | 63.0 | 1.11 | 16 | 45.6 | 46.8 |
| 2 | 1.3 | 8 | 63.0 | 1.66 | 16 | 46.4 | 48.7 |
| 3 | 1.3-1 | 8 | 53.5 | 0.31 | 16 | 43.9 | 46.3 |
| 4 | 2.2 | 8 | 123.0 | 1.91 | 16 | 111.2 | 113.5 |
| 5 | 2.3 | 8 | 127.5 | 1.38 | 24 | 111.6 | 114.8 |
| 6 | 2.4 | 8 | 129.0 | 1.05 | 36 | 111.8 | 114.0 |
| 7 | 2.5 | 8 | 131.0 | 2.29 | 36 | 112.3 | 116.8 |
| 8 | 2.6 | 8 | 118.0 | 2.92 | 42 | 113.5 | 120.2 |
| 9 | 2.7A | 8 | 264.0 | 0.92 | 36 | 197.0 | 202.8 |
| 10 | 2.7B | 8 | 261.0 | 1.25 | 36 | 197.0 | 200.0 |
| | | | | | 24 | 200.0 | 202.8 |
| 11 | 2.7C | 8 | 266.0 | 1.89 | 24 | 197.0 | 202.8 |
| 12 | 2.7D | 8 | 261.0 | 1.67 | 0 | --- | --- |
| 13 | 1.4 | 8 | 58.0 | 0 | 16 | 43.9 | 46.3 |

* Radial distance between terminus of hole and planned terminus measured normal to axis of hole.

Table 3

Field Drilling, Vertical Re-entry Holes

| No. | Station | Diameter in. | Depth ft |
|---|---|---|---|
| 1A | 1.2 | 3 | 74.6 |
| 2A | 1.3 | 3 | 74.6 |
| 5A | 2.3 | 3 | 108.2 |
| 7A | 2.5 | 3 | 107.0 |

Note: Holes 1A, 2A, 5A, and 7A were located 12 to 24 in. from holes 1, 2, 5, and 7, respectively, shown in table 2.

Table 4

Field Drilling, Horizontal Instrument Holes

| No. | Station | Diameter in. | Depth ft | Deviation* ft |
|---|---|---|---|---|
| 1 | 1.1-1 | 8 | 88.58 | 0 |
| 2 | 1.1-2 | 8 | 93.49 | 0.71 |
| 3 | 1.1-3 | 8 | 97.90 | 0.38 |
| 4 | 1.1-4 | 8 | 80.96 | 0.13 |
| 5 | 1.1-5 | 8 | 75.37 | 0.40 |
| 6 | 1.1-6 | 8 | 66.67 | 1.21 |
| 7 | 1.1-7 | 8 | 75.46 | 0.02 |
| 8 | 1.1-9 | 8 | 59.77 | 0.65 |
| 9 | 2.1-1 | 8 | 80.28 | 0.28 |
| 10 | 2.1-2 | 8 | 80.00 | 0.49 |
| 11 | 2.1-3 | 8 | 83.35 | 0.92 |
| 12 | 2.1-4 | 8 | 87.78 | 0.07 |
| 13 | 2.1-5 | 8 | 84.23 | 0.15 |
| 14 | 2.1-6 | 8 | 88.34 | 0 |
| 15 | 2.1-7 | 8 | 97.98 | 0.61 |
| 16 | 2.1-8 | 8 | 99.60 | 0.10 |
| 17 | 2.1-9 | 8 | 67.00 | 0 |
| 18 | 2.1-11 | 8 | 54.65 | 0.07 |
| 19 | 2.1-13 | 3 | 18.99 | 1.35 |
| 20 | 2.1-14 | 3 | 26.59 | 0.07 |
| 21 | 2.1-14 | 3 | 29.96 | 0.34 |
| 22 | 2.1-15 | 3 | 16.20 | 0.06 |
| 23 | 2.1-15 | 3 | 17.18 | 0.08 |
| 24 | 2.1-16 | 3 | 27.74 | 0.17 |

Note: Holes 20 and 22 were mislocated. Holes 21 and 23 were drilled in correct locations. In addition, two unnumbered 8-in.-diameter cable holes were drilled for a total depth of 218.40 ft.

* Radial distance between terminus of hole and planned terminus measured normal to axis of hole.

Table 5

Vertical Holes (for U. S. Bureau of Mines)

| No. | Station | Diameter, in. | Depth, ft |
|---|---|---|---|
| 1 | S-1 | 3 | 25.08 |
| 2 | S-2 | 3 | 24.59 |
| 3 | S-3 | 3 | 24.36 |
| 4 | S-4 | 3 | 24.32 |
| 5 | S-5 | 3 | 25.19 |
| 6 | S-6 | 3 | 25.03 |
| 7 | S-7 | 3 | 24.93 |
| 8 | S-8 | 3 | 25.14 |
| 9 | G-1 | 3 | 25.23 |
| 10 | G-2 | 3 | 25.50 |
| 11 | G-3 | 3 | 26.08 |
| 12 | G-4 | 3 | 26.38 |
| 13 | G-5 | 3 | 26.11 |
| 14 | G-6 | 3 | 25.90 |
| 15 | G-7 | 3 | 26.16 |
| 16 | G-8 | 3 | 26.17 |
| 17 | G-9 | 3 | 26.15 |
| 18 | G-10 | 3 | 26.18 |
| 19 | V-1 | 3 | 25.93 |
| 20 | V-2 | 3 | 25.94 |
| 21 | V-3 | 3 | 25.94 |
| 22 | A-1 | 3 | 25.90 |
| 23 | A-2 | 3 | 25.84 |
| 24 | A-3 | 3 | 25.82 |
| 25 | C-1 | 5 | 4.50 |
| 26 | C-2 | 5 | 5.50 |
| 27 | C-3 | 5 | 7.00 |
| 28 | C-4 | 5 | 1.00 |
| 29 | C-5 | 5 | 8.00 |
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| 39 | C-15 | 5 | 10.00 |

# APPENDIX A
## IN-PLACE ULTRASONIC VELOCITIES, PROJECT COWBOY AREA

### A.1 PURPOSE

Ultrasonic velocities of the in-place salt in the immediate areas of the 12- and 30-ft-diameter spherical cavities were obtained at the request of the Sandia Corporation and with the concurrence of all concerned.

### A.2 SCOPE

A total of 13 velocity-reading stations were established (see fig. A1).

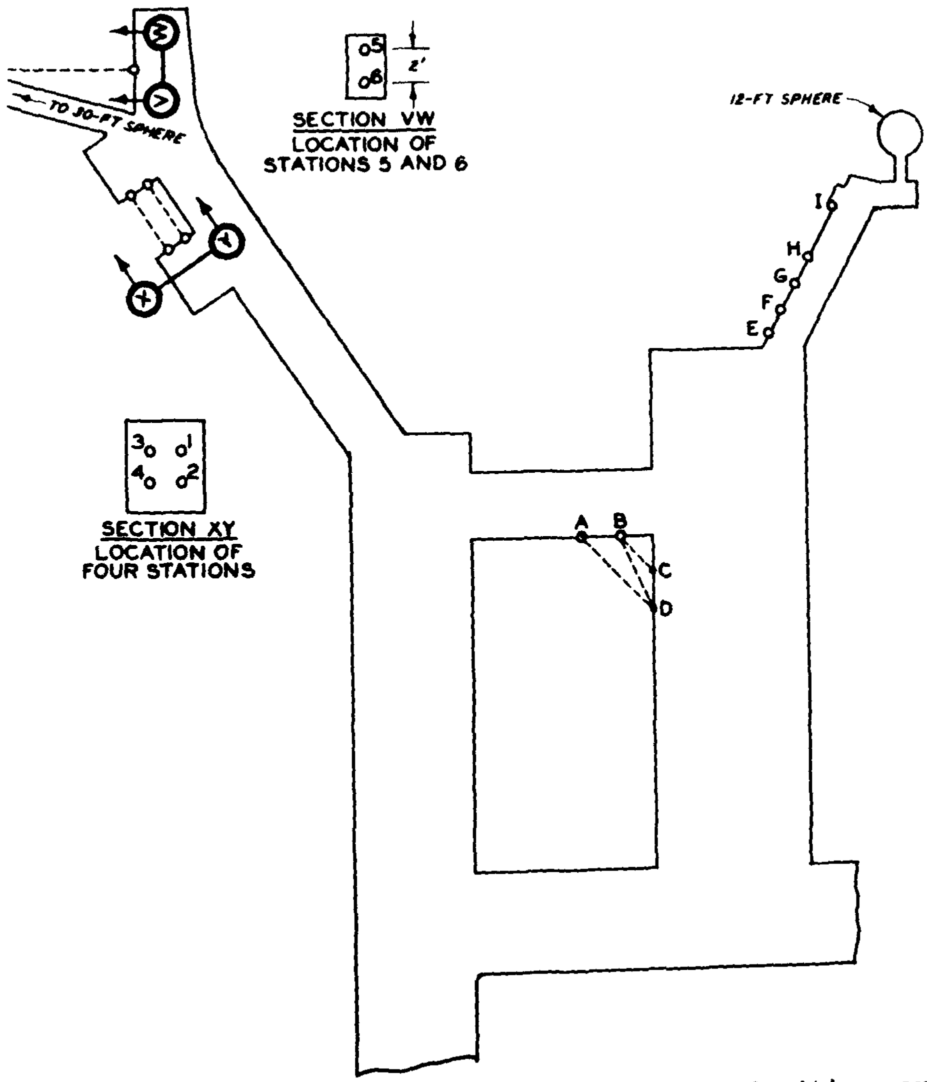


Fig. A1. Locations at which in-place ultrasonic velocities were measured, Project COWBOY area

Six of these stations, designated 1 through 6 and located at sections XY and VW, were established in the vicinity of the 30-ft sphere. The other seven, designated A through I, were located near the 12-ft sphere. The equipment and procedures used to obtain the readings are described in Method CRD-C 51-57, included at the end of this appendix (pages A4-A7).

## A.3 VELOCITY CALCULATIONS

The velocities were calculated from:

$$\text{Velocity} = \frac{\text{path length in feet}}{\text{effective time in seconds}}$$

## A.4 RESULTS

The results were as follows:

| Station | Effective Time microseconds | Path Length ft | Velocity fps |
|---|---|---|---|
| | 30-ft Sphere | | |
| 1 | 1940 | 15.5 | 7,990 |
| 2 | 1160 | 15.5 | 13,360 |
| 3 | 1150 | 15.5 | 13,475 |
| 4 | 1185 | 15.5 | 13,080 |
| 5 | 2925 | 42.36 | 14,480 |
| 6 | 3000 | 42.36 | 14,120 |
| | 12-ft Sphere | | |
| BC | 1160 | 14.919 | 12,860 |
| BD | 1425 | 18.8 | 13,200 |
| AD | 1725 | 23.13 | 13,410 |
| IE | 2905 | 41.5 | 14,285 |
| IF | 2610 | 36.5 | 13,985 |
| IG | 1550 | 21.5 | 13,870 |
| IH | 1185 | 16.5 | 13,925 |

The velocities obtained ranged in all cases except one from 12,860 to 14,480 fps. The one exception (7990 fps) was due to the crack known to exist in the path of this reading (station 1).

## A.5 DISCUSSION

Millican* gives the relation (taken from Wyllie, Gregory, and Gardner):**

$$\frac{1}{V_{log}} = \frac{\phi}{V_{liquid}} + \frac{1 - \phi}{V_{matrix}}$$

where:

$V_{log}$ = the ultrasonic velocity of the system as measured, fps
$V_{liquid}$ = the ultrasonic velocity of the interstitial fluid, fps
$V_{matrix}$ = the ultrasonic velocity of the rock, fps
$\phi$ = the fractional porosity

From the equation given in the preceding paragraph, it is possible by using either the typical velocity or the measured values to calculate the porosity of the salt. However, an assumption must be made if the interstitial fluid is air or brine or a combination of the two. It is believed that an air value of approximately 1100 fps and a water value of 4700 fps could be used. The reliability of the equation given above, however, is dependent upon correctness of the assumption that interface effects or other more complicated effects of inhomogeneity are negligible. This assumption is doubted and presently under study by several investigators.

---

* Marcus L. Millican, "The sonic log and the Delaware sand," Technical Note 2054, Petroleum Engineering, vol 12, No. 1 (January 1960), pp 71-75.

** M. R. J. Wyllie, A. R. Gregory, and L. W. Gardner, "An experimental investigation of factors affecting elastic wave velocities in porous media," Geophysics, vol 23, No. 3 (July 1958).

CRD-C 51-57

# METHOD OF TEST FOR PULSE VELOCITY OF PROPAGATION OF ELASTIC WAVES IN CONCRETE[1]

## Scope

1. (a) This method of test describes equipment and procedure for measuring the pulse velocity of propagation of compressional waves in concrete, for the purpose of obtaining a measure of the condition of the concrete. The method, which consists of determining the time of travel of a pulse or train of waves through a known path length in the material, may be used to advantage to indicate the progress of deterioration in concrete, in the study of setting behaviour, and in the survey of field structures for deterioration and cracking. The procedure is applicable to field or laboratory measurements without regard to size or shape of the specimen, within the limitations of presently available pulse sources of energy[2] and provided only that the length/width ratio of small specimens does not exceed a maximum figure.

(b) This method concerns itself with the measurement of the velocity of propagation of groups of compressional waves in concrete and does not apply to the propagation of groups of transverse or other vibrations in the material. The pulse velocity is independent of the dimensions of the body provided that reflected waves from boundaries do not interfere with the measurement of the arrival time of the directly transmitted pulse.

## Apparatus

2. The testing apparatus, shown schematically in Fig. 1, consists of the following:

(a) **Pulse Generator Circuit and Transducer.**- The pulse generator circuit shall consist of an electronic circuit for generating pulses of voltage and a transducer for transforming the electrical pulses into mechanical (ultrasonic) pulses. The electronic circuit shall produce repetitive pulses at a rate determined by the size of the specimen, and not less than 50 per second.

The transducer shall be constructed of piezoelectric or magnetostrictive material (Rochelle salt, quartz, barium titanate, etc.) suitably housed for mechanical protection. The resonant frequency of the transducer and mounting assembly shall be between 15,000 and 30,000 cp. It shall be provided with a suitable coupling medium in order to obtain adequate contact with the concrete. Use of a distended rubber diaphragm and an oil-filled housing under slight excess pressure has been found to be convenient; metal diaphragms may be used against smooth plane surfaces. The voltage output and impedance of the electronic circuit shall be designed for use with the piezoelectric material used. Voltage pulses of 500 to 1000 volts have been found satisfactory for use with 45-deg X-cut Rochelle salt crystals. The electronic circuits shall be such that the use of long connecting cables does not result in appreciable loss of voltage. Triggering voltages suitable for driving the oscilloscope

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[1] Based on a draft prepared by J. R. Leslie, Hydro-electric Power Commission of Ontario, 1952, published in ASTM *Bulletin* No. 204, Feb. 1955, p 19, and as Appendix to *Field Soniscope Tests of Concrete; 1953 Tests*, Waterways Experiment Station Technical Memorandum No. 6-383, Report No. 1, Apr. 1954.

[2] Presently available generators limit ranges to 3-in. minimum and 40-ft maximum. (Long, thin laboratory specimens exceeding a length/width ratio of 5/1 give poor results.)

Pulse velocities so measured may be expected to vary from a maximum of 18,000 fps for high strength concrete to 14,000 fps for average mixes, to a value less than 10,000 fps for specimens with advanced deterioration.

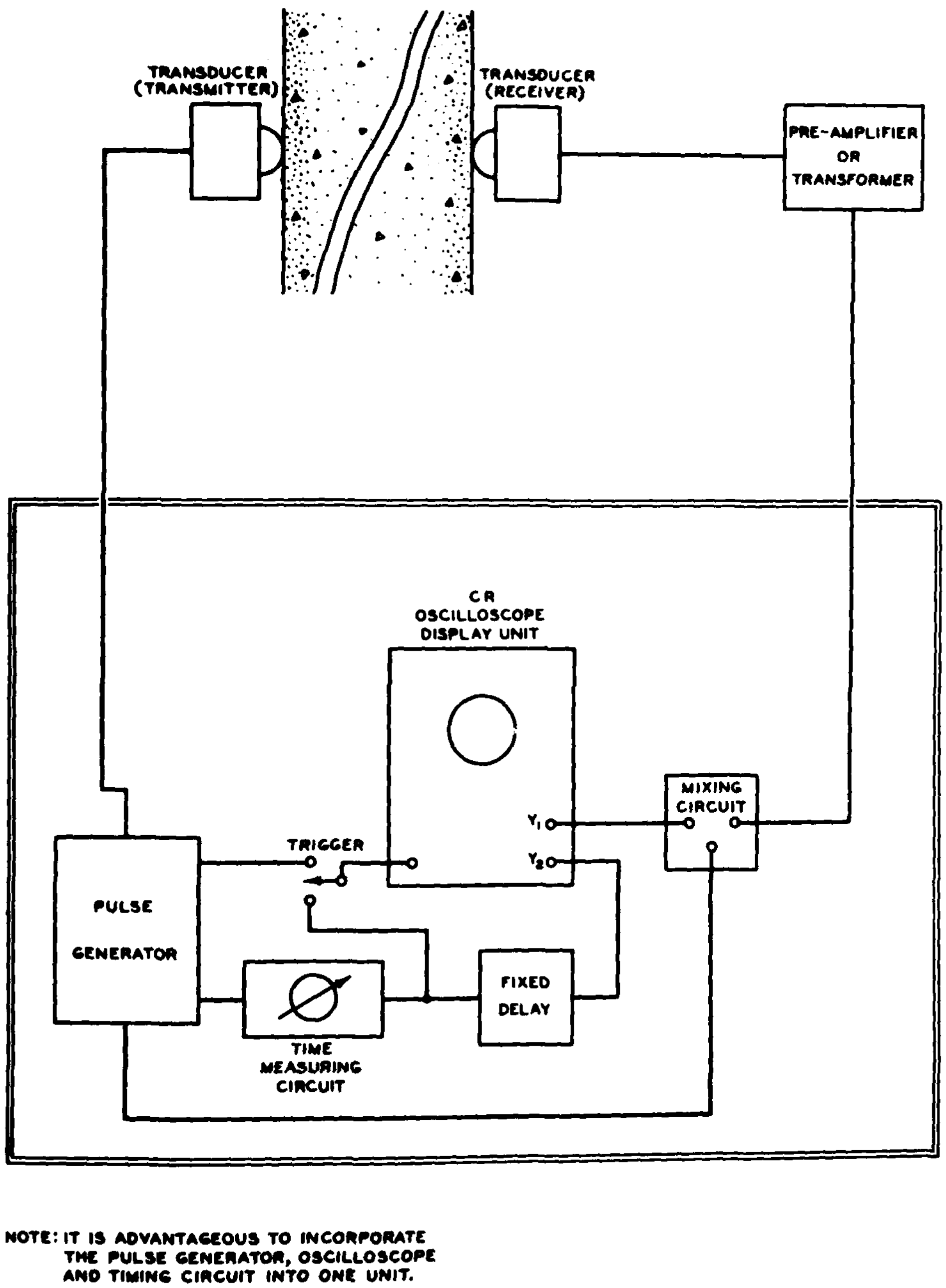


**Fig. 1. Schematic diagram of pulse velocity testing circuit**

and time delay circuits shall be suitably spaced in time and free from objectionable jitter.

**(b) Receiving Circuit and Transducer.-** The receiving circuit shall consist of a piezoelectric transducer with housing and an electronic amplifier. The piezoelectric transducer shall be so constructed that the resonant frequencies of the transmitter and receiver are the same. The use of a rubber-faced, oil-filled housing is recommended. The voltage generated at the receiver may be amplified in a suitable preamplifier or head amplifier, or may be matched to the connecting cable with a suitable transformer, prior to its transmission over connecting cables to the display unit. The amplifier or transformer shall have an essentially flat response between a frequency of 5 kilocycles and one ten times the resonant frequency of the transducers.

(c) **Display Unit.-** The display unit shall consist of a cathode-ray oscilloscope on which the transmitted and received pulses are viewed simultaneously as vertical deflections of the trace. The oscilloscope shall be provided with a triggered (driven) sweep circuit, operated from the pulse generator circuit via an interconnecting cable. The sweep circuit velocities shall be such that the time of travel through the material can be displayed with sufficient amplitude on the screen. Higher sweep velocities should be available to facilitate the accurate measurement of the time interval. This is achieved conveniently by the use of a delayed trigger circuit combined with an increase in the sweep velocity by a factor of four or more.

A vertical deflection amplifier shall be provided to which a connecting cable from the receiver may be connected. The frequency response of this amplifier shall be similar to that given in subparagraph (b) above.

The over-all amplifier gain shall be sufficient to allow full deflection of the weakest signals which are received. An approximate gain of 200,000 maximum including the preamplifier has been found sufficient for use with Rochelle salt receivers.

An intermixing circuit shall be provided to allow a fraction of the transmitted pulse to pass through the vertical amplifiers.

The cathode-ray tube may be of the single- or double-beam type. If a single-beam type is used, means must be provided for superimposing a timing wave or marker pulse on the trace in addition to the signal from the receiver.

(d) **Time Measuring Circuit.-** The time measuring circuit shall be capable of measuring intervals between 100 microseconds and 5 milliseconds to a precision of one part in 200. It should be provided with multiple scales in order that the desired accuracy can be obtained. It should be initiated by a triggering voltage from the pulse generator circuit and should operate at the repetition frequency of the latter. The timing circuit should provide an output marker pulse or "strobe" at the end of the delay period which can be observed on one of the cathode-ray tube traces as a reference marker.

The marker pulse shall be continuously adjustable in position by means of a calibrated dial. The use of a multiturn potentiometer equipped with a dial divided into 1000 divisions is recommended. The calibration of delay time against dial divisions should be essentially linear in order that the latter may be direct reading in time intervals. Ranges of 200, 1000, and 5000 microseconds full-scale have been found convenient for use with both laboratory specimens and field structures although the latter range may be omitted for laboratory use. The time measuring circuit should be reasonably insensitive to thermal and line voltage changes.

Provision of a calibration device for the purpose of checking the linearity and range of the time measuring circuit is recommended. One form of calibrator widely used consists of a quartz crystal oscillator with a frequency of 100 kilocycles, synchronized with the pulse generator circuit. The calibrator is connected to the vertical amplifier for use.

The general principles in the design of precision time-delay and calibrator circuits are to be found in the following references:

F. C. Williams and H. F. Moody, "Ranging Circuits, Linear Time-base Generators and Associated Circuits," *Journal* IEE (London), Vol 93, Pt IIIA No. 7, 1946, p 1188.

"Waveforms," MIT series, McGraw-Hill Book Co., 1949, Vol 19, Chapters 5 and 9.

"Electronic Time Measurements," MIT Series, McGraw-Hill Book Co., 1949, Vol 20.

## Test Procedure

3. **(a) Determination of Zero Correction.**- A zero correction must be applied to the measured time intervals. The zero correction is equal to the travel time in the rubber and oil paths in the transducers. It may be measured directly by pressing the two transducers together with the same pressure (Note) used in the actual measurement, and measuring the time on the cathode-ray tube.

Note.- A ring of sheet cork attached to the rim of each transducer will enable the transducers to be employed in a more uniform manner. The cork ring must be sufficiently thin so as not to interfere with the operation of the pressure switch.

**(b) Determination of Travel Time in Concrete.**- The rubber faces of the transducers are pressed against the faces of the concrete after wetting the latter with water or oil to exclude entrapped air from the surface of the concrete. The length of the shortest direct path between the centers of the diaphragms is then measured and the time of travel measured on the cathode-ray tube by aligning the strobe marker pulse opposite the received wave front and reading the calibrated dial.

Because the effective beam width of the transducers is wide they need not be pointing at each other. Transmission times can be measured across corners of structures or along one face, although in the latter case the maximum range is reduced.

For greatest accuracy in the time measurement the amplifier gain should be increased until the wave front of the received signal is essentially vertical. The error due to rounding off of the received wave is then minimized. The use of the sweep expansion circuit will result in an increase in the accuracy of measurement under most conditions of measurement.

Pulse velocity measurements on large structures require the use of long interconnecting cables. The latter should be the low-capacity, shielded, coaxial type. The use of field telephones between the stations has been found to expedite readings.

## Calculations

4. The velocity is obtained from the formula

$$V = \frac{L}{T} \text{ ft/sec}$$

where:

L = path length in feet,

T = effective time (seconds) or measured time minus zero correction.

# APPENDIX B
## PHYSICAL PROPERTIES TESTS OF SALT CORES

### B.1 PURPOSE

Tests on salt cores were conducted to provide information on the physical characteristics of the salt formation in the Project COWBOY area of the Carey Salt Mine for the various agencies participating in the project.

### B.2 SCOPE

Three cores were obtained from the salt in Drift A of the mine (for location of Drift A, see fig. 1 of main text). Two of these cores were a nominal 6 in. in diameter and the third was a nominal 2 in. in diameter. The cores were brought to the WES laboratory where the 6-in.-diameter cores were sawed into two cores (A and B) 12 in. in length, and the 2-in. core was sawed into two 4-in.-long cores (C and D). The physical tests performed are listed in table B1.

### B.3 RESULTS

The test results are given in table B1 and fig. B1.

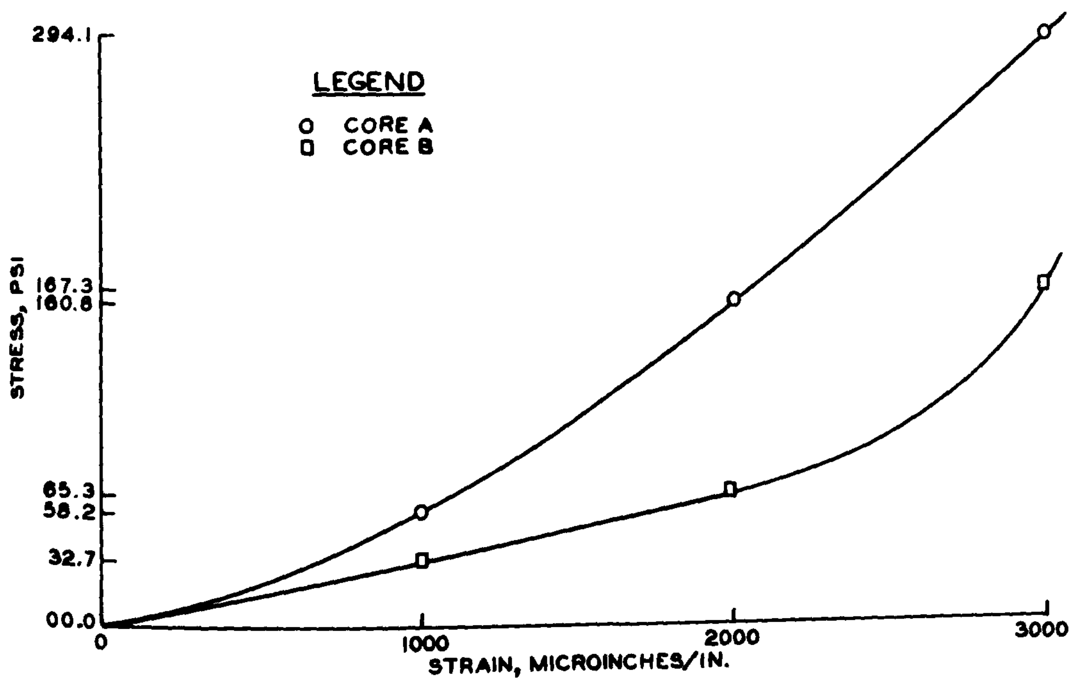


Fig. B1. Results of static tests of 6-in. saltcrete cores

## B.4 DISCUSSION

Previous materials tested by both sonic and ultrasonic methods indicate that the sonic velocity is always numerically lower than the ultrasonic.

One end of the salt in core B was discolored and appeared to have been penetrated by water. An examination indicated that considerable clay had penetrated the salt crystals in this end of the core. A cursory examination did not indicate any apparent difference in the halite-anhydrite ratio between the two cores; however, both were very coarse grained and contained numerous incipient fractures. This may account in part for some of the difference in test values between cores A and B.

Table B1

Results of Tests of Salt Cores, Project COWBOY

| | Core A | Core B | Core C | Core D |
|---|---|---|---|---|
| (1) Weight of core, g | 10,646 | 10,667 | -- | -- |
| (2) Length of core, in. | 12.4 | 12.4 | 4 | 4 |
| (3) Diameter of core, in. | 5.7 | 5.7 | 2.12 | 2.12 |
| (4) Bulk specific gravity | 2.167 | 2.168 | -- | -- |
| (5) Fundamental transverse frequency, cycles/sec (vibrating cores) | 3,385 | 3,200 | -- | -- |
| (6) Fundamental longitudinal frequency, cycles/sec (vibrating cores) | 5,575 | 4,994 | -- | -- |
| (7) Fundamental torsional frequency, cycles/sec (vibrating cores) | 3,886 | 3,745 | -- | -- |
| (8) Sonic velocity, fps (from (6) and (2)) | 11,095 | 9,938 | -- | -- |
| (9) Ultrasonic velocity, fps (time of transmission of pulse through length of core) | 12,345 | 11,055 | -- | -- |
| (10) Dynamic modulus of elasticity, psi (from (1) and (5)) | $0.384 \times 10^6$ | $0.344 \times 10^6$ | -- | -- |
| (11) Poisson's ratio (from (8) and (9)) | 0.27 | 0.27 | -- | -- |
| (12) Static modulus of elasticity, psi (compressometer method) | $0.89 \times 10^6$ | $0.50 \times 10^6$ | -- | -- |
| (13) Compressive strength, psi | --- | 2,620 | -- | 2,740 |
| (14) Tensile strength, psi (splitting) | 210 | --- | 405 | -- |

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